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.CaBaCuO HIGH Tc SUPERCONDUCTING MICROSTRIP RING RESONATORS DESIGNED FOR 12 GHZ

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ABSTRACT

Microwave properties of sputtered Tl-Ca-Ba-Cu-O thin films were investigated by designing, fabricating and testing microstrip ring resonators. Ring resonators designed for 12 GHz fundamental resonance frequency, were fabricated and tested. From the unloaded Q values for the resonators, the surface resistance was calculated by separating the conductor losses from the total losses. The penetration depth was obtained from the temperature dependence of resonance frequency, assuming that the shift in resonance frequency is mainly due to the temperature dependence of penetration depth. The effective surface resistance at 12 GHz and 77 K was determined to be between 1.5 and 2.75 mΩ, almost an order lower than Cu at the same temperature and frequency. The effective penetration depth at 0 °K is approximately 7000 Å.

1. INTRODUCTION

Among the high Tc materials, thallium based superconductors are very attractive for elecronic applications, as they have shown the highest Tc[1], high Jc[2-3], and the lowest values for microwave surface resistance(Rs)[3-4]. The foremost applications of high Tc thin films is expected to be in the area of 'passive microwave devices' such as resonators, filters and delay lines. High Tc superconductors have a greater impact on passive microwave devices because of their lower surface resistance in thin films of high Tc superconductors, compared to Cu and Au, corresponding to higher Q and improved performance in passive microwave devices. The second advantage is the frequency independent penetration depth as compared to frequency dependent skin depth in normal conductors. This means, dispersion introduced in superconducting components will be negligible upto frequencies as high as 1 THz. Compact delay lines[5], filters[6], and resonators are possible, with lower losses.

This paper addresses the design, fabrication and characterization of $Tl_2Ca_1Ba_2Cu_2O_x$ (2122) thin film based microstrip ring resonators.

2. EXPERIMENTAL

A microstrip ring structure resonates if its electrical length is an integral multiple of the guide wavelength. A simple ring resonator device was designed which consisted of a ring structure separated from the feed line by a small coupling gap. The size of the coupling gap determines the coupling between the feed line and the ring resonator. A ring resonator designed for 10 mil thick $LaAlO_3$ substrates ($\epsilon_r = 24.5$), for a fundamental resonance at 12 GHz is shown in figure 1.

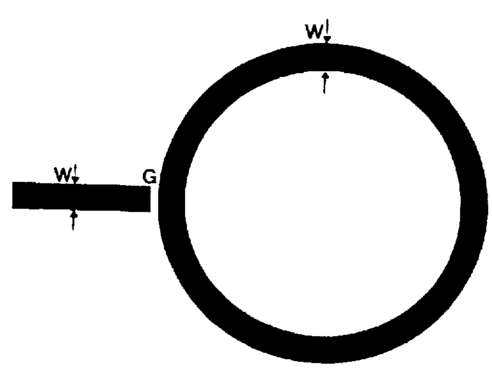

Fig.1 The ring resonator device designed for 12 GHz resonance

In the figure, the linewidth of the ring and the microstrip feed line is W = 5.6 mils, the coupling gap G = 1.75 mils, and the mean radius of the ring $R = (R_1 + R_2)/2 = 77$ mils. The characteristics impedance of the microstrip is 41 Ohms at 12 GHz. The design of the ring resonator has been described by Chorey et al[7].

TlCaBaCuO ring resonators were fabricated by patterning 0.3 μm thin films using AZ 1421 positive photoresist photolithography and wet chemical etching techniques. The fabrication and patterning of TlCaBaCuO thin films is described in detail elsewhere[8]. The ring resonators were annealed using our standard annealing procedures[8-9]. The samples were divided into two groups: one set of samples with 1 μm gold film on the bottom side of the $LaAlO_3$ substrate for the ground plane formation and the second set with 0.3 μm TlCaBaCuO superconducting thin film ground plane. The ground plane side superconductor was deposited and post-processed using our routine post-deposition methods, after the microstrip ring resonator was fabricated on the top side.

A ring resonator was mounted in a gold plated Copper test fixture of 1" wide, 2" long and 1" thickness. The test fixture was placed on the cold head of the helium gas closed cycle cryogenic system. Connections to the HP 8720 network analyzer were made using a 0.141" semi-rigid co-axial cable of 50 ohms characteristic impedance. Before measurements were performed on ring resonators, standard one port calibration was performed at room temperature.

The resonator quality factor(Q) was obtained from the swept frequency reflection measurements[7,10]. The unloaded Q is obtained by separating the external losses in the feed line and due to coupling. The loaded Q and the unloaded Q are related through the reflection coefficients at resonance and far from the resonance[10]. The determination of whether the resonator was overcoupled or undercoupled was made from the Smith chart and also the phase response of the resonator. Typically, the ring resonators were overcoupled. Measurements for the superconducting resonator were performed at the fundamental resonance frequency of 12 GHz, and an input power level of -30 dBm.

3. RESULTS

Unloaded Q versus temperature characteristics for an all-superconducting ring resonator is shown in figure 2. The curve A is the data for the high Tc thin film ring resonator with a superconducting ground plane. For comparison, data for the gold resonator is also shown in curve B.

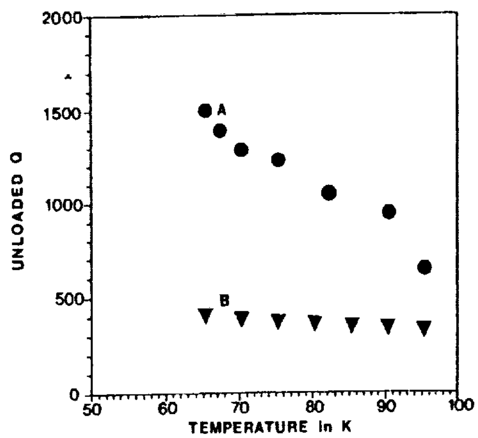

Fig.2. The unloaded Q vs Temperature for an all-superconducting resonator

The unloaded Q of the ring resonator with superconducting ground plane is approximately four times higher than the gold resonator at 65 °K. In addition, the unloaded Q of the superconducting ring resonator shows an increasing trend in Q with decreasing temperature, whereas the superconducting ring resonators with gold ground plane show a saturation of Q at low temperatures due to the dominance of ground plane conductor losses.

The effective surface resistance (R_s) of the superconducting thin films, were obtained from ring resonator quality factor (Q) measurements. By separating the conductor and dielectric losses, the Rs was calculated using the standard microstrip loss equations described by Pucel et al[11]. The Rs at 12 GHz, and 77 °K was determined to be typically between 1.5 and 2.75 mΩ, almost an order lower than Rs of Cu at the same temperature and frequency. The swept frequency reflection measurements performed at several temperatures, is also used in determining the penetration depth of the TlCaBaCuO superconducting thin films. The resonance frequency was measured at each temperature for ring resonators. A typical measured resonance frequency shift with respect to temperature for a superconducting ring resonator with approximately 1 μm thick gold ground plane is shown in figure 3.

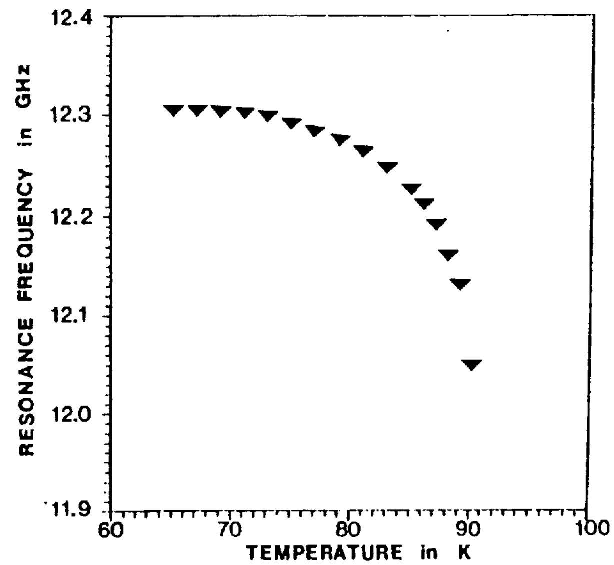

Fig.3. Resonant frequency vs Temperature characteristics for a resonator

The shift in resonance frequency with temperature is mainly due to the temperature dependence of the penetration depth of the superconductor. Thus, the resonance frequency shift is an indirect method of determining the penetration depth. From the figure, the change in resonance frequency below 70 °K is almost negligible. The detailed analysis of this figure to determine the penetration depth of the superconducting thin films, is given in the next section.

4. ANALYSIS AND DISCUSSIONS

The phase velocity of a superconducting microstrip transmission line with a superconducting ground plane is given by[12],

$$v_{ph} = c/\sqrt{\epsilon_{eff}} * \{1 + 2*\lambda/h*\coth(t/\lambda)\}^{-0.5} \qquad \text{--->(1)}$$

where c is the velocity of light, ϵ_{eff} is the effective dielectric constant, h is the substrate thickness, t is the thickness of the microstrip, λ the penetration depth of the superconducting microstrip. The penetration depth is temperature dependent based on the Gorter-Casimir relationship[13] ie.,

$$\lambda(T) = \lambda(0)*[1-(T/Tc)^4]^{-0.5} \quad \text{---> (2)}$$

for temperature T less than Tc. $\lambda(0)$ is the penetration depth at T=0 °K. The resonance frequency of the ring resonator is given by the equation

$$f = n*v_{ph}/(2*L) \quad \text{---> (3)}$$

where f is in GHz, L is the mean circumference of the ring in mm, and n is the integer order of resonance. From the temperature dependence of resonance frequency measurements and the above equations, the best value of $\lambda(0)$ was determined to be 6890 Å. The typical value ranges between 7000 Å and 8000 Å. Since the thin films are only 0.3-0.4 μm thick, the penetration depth depends upon the properties of the superconductor through the entire film.

A theoretical model based on the Phenomenological loss Equivalence Method (PEM) approximation[14-15] was employed to determine the theoretical variation of conductor losses with temperature for the cases of superconducting microstrip/gold ground plane, and superconducting microstrip/superconducting ground plane. Both these cases were compared to the attenuation constant of a gold microstrip on $LaAlO_3$ substrate.

The attenuation constant for a superconducting microstrip is calculated from the formula[15],

$$\alpha = (T/Tc)^4/[1-(T/Tc)^4]^{3/2} * G_1/4 * \sigma_n/Z* w^2* \mu^2 * \lambda(0)^3* \coth(X)$$
$$+ X \operatorname{cosec}^2(X) \quad \text{Np/m} \quad \text{---> (4)}$$

where $X = A * G_1/\lambda(0) * [1-(T/Tc)^4]^{1/2}$.

G_1 is the geometric factor given by the equation

$$G_1 = 1/(\pi h)*[1-(W_e/(4h))^2]*[1/2+h/W_e+h/(\pi W_e)*\ln(2h/t) \quad \text{---> (5)}$$

W_e is the effective width of the microstrip, and A is the area of cross-section of the microstrip, T is the measurement temperature below Tc, and $\lambda(0)$ the penetration depth at 0 °K of the superconductor.

The parameters assumed for the calculations are the relative dielectric constant (ϵ_r) of $LaAlO_3$ to be 24.5[7], the loss tangent (tan δ) of $LaAlO_3$ to be $8.3*10^{-5}$ below 100 °K[7], the substrate thickness (h) of 10 mil, the width of the microstrip (W) of 142 μm, corresponding to a characteristic impedance of 41 ohms at 12 GHz, the thickness of the superconducting microstrip(t) to be 0.3 μm, the ground plane thickness of 1 μm for gold ground plane and 0.3 μm for superconducting ground plane, the zero resistance Tc of the TlCaBaCuO thin films was to be 100 °K, and the normal conductivity at Tc (σ_n) of $1.5*10^6$ S/m.

The ground plane conductor losses can be calculated by the same method, using the geometric factor G_2 instead of G_1 in the equation 4.

$$G_2 = 1/(2\pi h) * [1-(W_e/4h)^2] \quad \text{---> (6)}$$

Figure 4 shows temperature variation of the attenuation due to conductor losses for a gold microstrip (curve A), a superconducting microstrip with a gold ground plane (curve B), and a superconducting microstrip with a superconducting ground plane (curve C) as determined using equations 4-6.

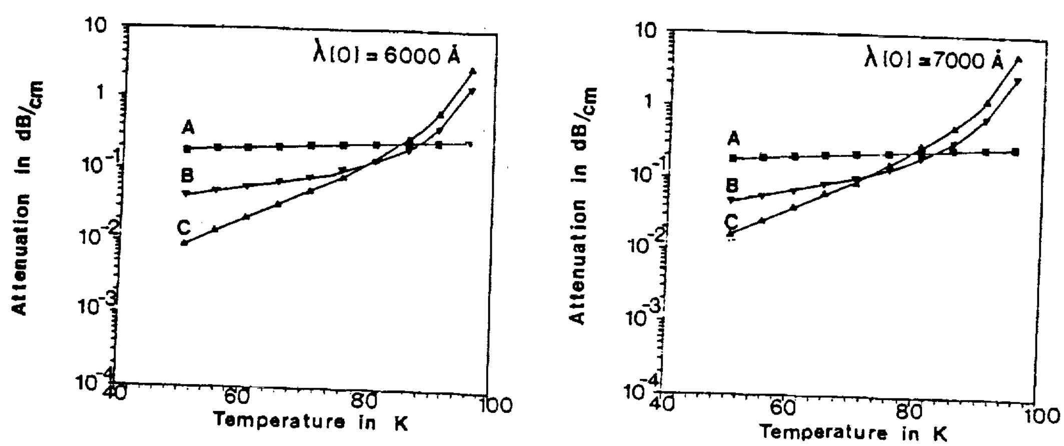

Fig.4. Theoretical attenuation loss vs temperature characteristics for superconducting microstrip with gold ground plane (B), and superconducting ground plane (C), compared to a gold microstrip (A).

The diagram in the left is for $\lambda(0)$ of 6000 Å, and the one in the right is for $\lambda(0)$ of 7000 Å. The figures show lower attenuation for the microstrip with superconducting ground plane (curve C) compared to the one with gold ground-plane (curve B), below 77 °K.

The surface resistance of the superconducting thin film can be obtained from the attenuation equation

$$R_s = 2\, Z_0\, \alpha / G_1 \qquad \text{---> (7)}$$

where Z_0 is the characteristic impedance of the microstrip.

The microwave properties of TlCaBaCuO thin films obtained from the ring resonator measurements were used in designing a reflection type hybrid phase shifter circuit based TlCaBaCuO thin film components and GaAs MESFETs. The design of the superconducting microstrips included the effects due to complete field penetration in the films. The phase bits were designed for 90 and 180 degrees phase shift, operating at 4 GHz center frequency, 25% bandwidth and phase error less than 5 degrees. Each phase bit consists of a 3 dB Lange coupler, impedance transforming networks and GaAs MESFET switches. A 180 degrees phase bit circuit was fabricated and tested using gold microstrip. The circuit showed a phase shift of 180.06 degrees at 3.9277 GHz. The insertion loss of the circuit was as low as -2.12 dB in the off state of the switching devices, and -2.523 dB in the on state. The input and output reflection losses were above 10 dB. The results of the superconductor/semiconductor hybrid phase shifters will be published elsewhere[16].

5. SUMMARY

The microwave properties of TlCaBaCuO thin films were investigated by designing, fabricating and characterizing a microstrip ring resonator. The resonator was designed for a fundamental resonance frequency of 12 GHz, and for fabrication on 10 mil thick $LaAlO_3$ substrates. Ring resonators with gold ground plane of 1 μm thickness and TlCaBaCuO superconducting ground plane of 0.3 μm thickness were fabricated and characterized at cryogenic temperatures. The unloaded Q for the superconducting resonators were above 1500 at 65 °K, compared to 370 for a gold resonator. The surface resistance of the TlCaBaCuO thin films obtained by separating conductor losses from the Q measurements is typically between 1.5 and 2.75 m-Ohms at 12 GHz and 77 °K, almost an order lower than Cu and Au at the same temperature and frequency. The penetration depth at 0 °K, was calculated from the resonance frequency shift with temperature measurements. The typical values for the penetration depth at 0 °K is approximately between 7000 and 8000 Å.

The conductor losses in the superconducting microstrips with superconducting ground plane were compared to the ones with gold ground plane using a theoretical model called the Phenomenological loss Equivalence Method (PEM). This model predicted lower conductor losses for the microstrip with superconducting ground plane, below 77 °K.

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Conductor-Backed Coplanar Waveguide Resonators of $YBa_2Cu_3O_{7-\delta}$ on $LaAlO_3$

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***Abstract*— Conductor-backed coplanar waveguide (CBCPW) resonators operating at 10.8 GHz have been fabricated from laser ablated and off-axis magnetron sputtered $YBa_2Cu_3O_{7-\delta}$ (YBCO) high-temperature superconducting (HTS) thin films on $LaAlO_3$. These resonators were tested in the temperature range from 14 to 92 K. The unloaded quality factor (Q_0) at 77 K of the HTS CBCPW resonators was 3 to 4 times that of a similar gold (Au) resonator. To our knowledge, these results represent the first reported measurements of HTS-based CBCPW resonators.**

I. Introduction

The coplanar waveguide (CPW) structure is advantageous for HTS-based microwave IC fabrication mainly because of its geometrical attribute of having the signal ground planes on the same surface as the signal transmission line [1]–[3]. To improve thermal contact between the substrate of the CPW and the cooling fixture, a layer of a good conducting material can be deposited onto the reverse side of the substrate. This conducting layer also acts as an additional ground plane for the structure. When such a ground plane is added, the resulting structure is known as a conductor-backed coplanar waveguide (CBCPW). To date, coplanar superconducting circuit tests have been reported for structures without a back-ground plane, and only at 77 K and 4.2 K [1]–[4]. This letter represents the first report of measurements on several $YBa_2Cu_3O_{7-\delta}$ (YBCO) HTS-based CBCPW resonators from 14 K to 92 K and at 10.8 GHz. The performance of these resonators, as compared with that of an Au-based counterpart is presented.

II. Experimental

The CBCPW resonators analyzed in this study were patterned on laser ablated and off-axis magnetron sputtered $YBa_2Cu_3O_{7-\delta}$ (YBCO) thin films on 1.0 × 1.0 × 0.05 cm (100) $LaAlO_3$ substrates. A schematic of the CBCPW resonator is shown in Fig. 1. This pattern was transferred to the HTS films using standard photolithography techniques and a subsequent "back-etching" process using a 1% phosphoric acid (H_3PO_4) solution. Afterwards, the ground plane on the opposite side of the substrate was formed by evaporation of a Au layer ~2.5 μm thick on top of a Chromium layer (~150 Å) previously evaporated on the $LaAlO_3$ to improve Au adhesion. For comparison purposes, a similar resonator was made with its CPW part consisting of an evaporated Au layer ~1.2 μm thick. The length (L2) and width (S) of the center conductor were 7.020 mm and 0.200 mm, respectively. The gaps on each side (W) and at the bottom (G2) of the resonator were 0.530 mm, and G3 was 0.630 mm. The coupling between the external coaxial lines and the resonator was achieved through an SMA launcher. The center pin of the connector was placed in direct contact with the feed line that tapered from 0.559 mm to the width of the center conductor over a length L1 of 1.000 mm. Coupling to the resonator was achieved across a gap (G1) 0.050 mm wide. To improve the contact between the launcher and the feed line, silver (Ag) contacts (~2500 Å thick) were evaporated onto the end of the feed line and the coplanar ground planes. The transition temperature ($T_c(R{=}0)$) of the resonators after being patterned was measured using standard four-point probe techniques. The measured T_c values were 91.1 K, 89.9 K, and 84 K, for samples 1 (laser ablated), 2 (magnetron sputtered), and 3 (laser ablated), respectively. Each resonator was mounted on a brass test fixture which was bolted to the cold finger of a close-cycle-helium-gas refrigerator and enclosed inside a vacuum can. The reflection coefficient of the circuit was measured using an HP-8510C network analyzer, and was used to determine the unloaded quality factor (Q_0) of the resonator according to the procedure described in [5]. The network analyzer was calibrated with short, open, and load standards before the beginning of each measurement cycle.

III. Results

The results of the measurements on the CBCPW resonators are summarized in Table I. Films thickness and T_c values were measured after patterning. The Q_0's versus temperature for the resonators tested in this study are shown in Fig. 2. The results show that sample 2 has the highest Q_0 values for the temperature range in common for all the resonators. Its Q_0 at 77 K and 10.8 GHz was 470, which is approximately four times better than that of the Au resonator at the same temperature and frequency. However, this value is approximately 0.4 of the best reported value for laser ablated YBCO-based CPW structures at 8.8 GHz and 77 K [6]. This reduction may be due to the effect of adding a back conductor.

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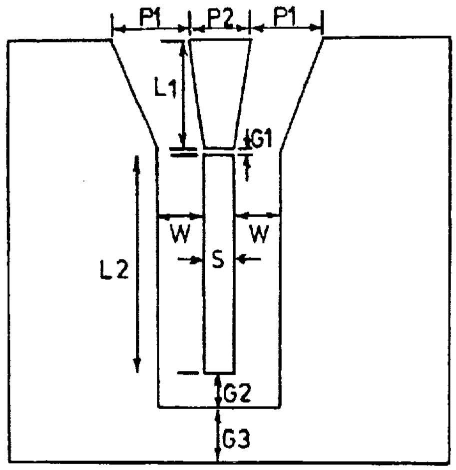

Fig. 1. Top view of the conductor-backed coplanar waveguide (CBCPW) resonator (9.230 × 9.230 mm). P1 = 0.533 mm, P2 = 0.559 mm, L1 = 1.000 mm, L2 = 7.020 mm, W = 0.530 mm, S = 0.200 mm, G1 = 0.050 mm, G2 = 0.530 mm, and G3 = 0.630 mm. The relative dielectric constant (ϵ_r) of the substrate is 22.

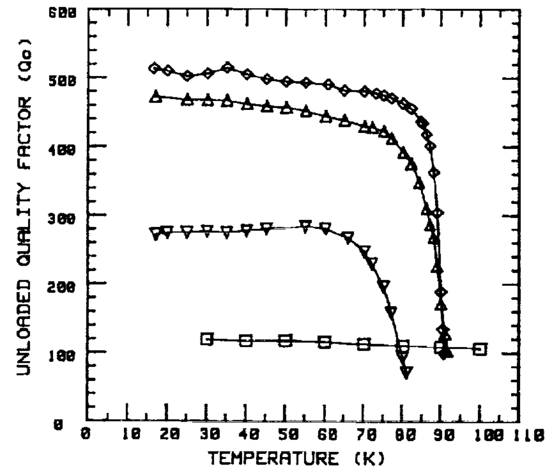

Fig. 2 Unloaded quality factor (Q_0) versus temperature for a Au (□), and YBCO CBCPW resonators on $LaAlO_3$; sample 1 (△; laser ablated), sample 2 (◇; off-axis magnetron sputtered), sample 3 (▽; laser ablated).

TABLE I
FILM PROPERTIES OF CONDUCTOR-BACKED COPLANAR WAVEGUIDE RRESONATORS

Sample	Deposition Temp. (°C)	Film Thickness (nm)	T_c(K)[a]	Q_0(77 K)[b]	f_0(GHz; @ 77 K)[c]
Au		1200		110	10.803
1	715	350	91.1	412	10.805
2		350	89.9	470	10.755
3	715	310	84.0	159	10.662

[a] dc transition temperature.
[b] Unloaded quality factor.
[c] Resonance frequency.

For microwave applications an HTS-based resonator should be characterized by a high T_c (~90 K), a rapid increase in Q_0 as the sample is cooled below T_c, and a fast stabilization of the Q_0 with respect to temperature at temperatures not far below T_c. Of the three resonators under study, samples 1 and 2 seem to satisfy these demands. However, although resonances for samples 1 and 2 were observed around the same temperature (~91 K), the increase in Q_0 with decreasing temperature for sample 1 is not as sharp as that for sample 2. The behavior of sample 1 as compare with sample 2 could be associated with a higher degree of homogeneity for the sputtered film than that attained for the laser ablated one for which the more gradual change of the Q_0 with temperature may be a consequence of a distribution of T_c's from grain to grain and other film inhomogeneities. However, the closeness of the Q_0 values for these samples indicates that films suitable for microwave applications can be obtained by off-axis magnetron sputtering as well as laser ablation.

IV. CONCLUSION

Conductor-backed coplanar waveguide (CBCPW) resonators have been patterned on laser ablated and off-axis magnetron sputtered YBCO HTS thin films on $LaAlO_3$. These resonators were tested in the temperature range from 14 to 92 K and an unloaded quality factor Q_0 as high as 470 was obtained at 10.8 GHz and 77 K. This value is four times higher than that of a similar all Au resonator at the same frequency and temperature. We found that similar Q_0 values were obtained for CBCPW resonators fabricated on both off-axis magnetron sputtered and laser ablated YBCO thin films of comparable T_c's.

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CONDUCTOR-BACKED COPLANAR WAVEGUIDE RESONATORS OF Y-Ba-Cu-O AND Tl-Ba-Ca-Cu-O ON $LaAlO_3$

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Abstract--Conductor-backed coplanar waveguide (CBCPW) resonators operating at 10.8 GHz have been fabricated from Tl-Ba-Ca-Cu-O (TBCCO) and Y-Ba-Cu-O (YBCO) thin films on $LaAlO_3$. The resonators consist of a coplanar waveguide (CPW) patterned on the superconducting film side of the $LaAlO_3$ substrate with a gold ground plane coated on the opposite side. These resonators were tested in the temperature range from 14 to 106 K. At 77 K, the best of our TBCCO and YBCO resonators have an unloaded quality factor (Q_o) 7 and 4 times, respectively, larger than that of a similar all-gold resonator. In this study, the Q_o's of the TBCCO resonators were larger than those of their YBCO counterparts throughout the aforementioned temperature range.

I. INTRODUCTION

Since their discovery in 1986, high transition temperature superconducting (HTS) compounds have been employed in the development of passive microwave transmission structures such as resonators, filters, and delay lines [1-3]. Ease of fabrication and performance reliability are two requirements that these HTS compounds should meet in order to be used in microwave circuits. Because of its geometrical attribute of having the ground planes on the same surface as the signal transmission line, coplanar waveguide (CPW) structures are advantageous for HTS-based microwave integrated circuits. When a good conducting layer is deposited on the opposite side of the CPW supporting substrate the structure is known as a conductor-backed coplanar waveguide (CBCPW).

Recently, reports on YBCO-based CPW and CBCPW resonators have been published [4-7]. Until now, a comparative study to determine which type of HTS compound is more appropriate for the optimization of these structures for microwave applications has not been done. In this paper we present our results on the performance of CBCPW resonators fabricated from TBCCO and YBCO thin films on $LaAlO_3$.

II. EXPERIMENTAL

Figure 1 shows a schematic representation of the CBCPW resonators analyzed in this study. The TBCCO resonators were custom made by Superconductor Technologies Inc. from laser ablated films (~800 nm thick) deposited onto 1.0x1.0x0.05 cm (100) $LaAlO_3$ substrates. The YBCO resonators were patterned by us on laser ablated (NASA-Lewis) and magnetron sputtered (Conductus Inc.) thin films (~350 nm) on $LaAlO_3$ substrates of the aforementioned dimensions and crystallographic orientation. The pattern shown in Fig. 1 was transferred to the HTS films using standard photolithography techniques followed by a "back-etching" process using a 1% phosphoric acid (H_3PO_4) solution. The ground plane on the opposite side of the substrate was formed by successive evaporations of a 150 Å thick chromium layer and a ~2.5 μm thick gold layer. A similar all-gold CBCPW resonator, with its CPW layer ~ 1.2 μm thick, was also fabricated for comparison purposes. The testing of the resonators was done by mounting them on a brass test fixture bolted to the cold finger of a closed-cycle-helium-gas refrigerator and enclosed inside a vacuum can with feedthroughs to allow coupling between the resonator and a coaxial waveguide. The coupling between the coaxial line and the resonators was achieved through an SMA launcher. The center pin of the connector was placed in direct contact with the feed line that tapered from 0.559 mm to the width of the center conductor over a length (L1) of 1.000 mm. Coupling to the resonator was achieved across a gap (G1) 0.050 mm wide. The reflection coefficient of the resonators was measured using an HP-8510C network analyzer, and was used

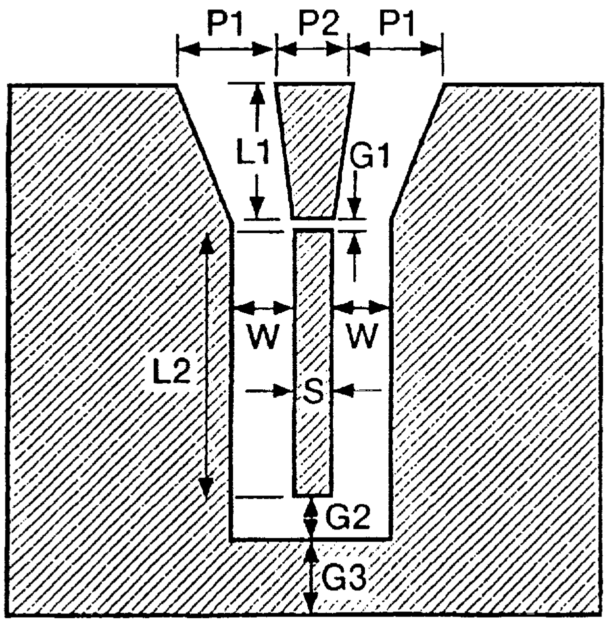

Fig. 1 Top view of the conductor-backed coplanar waveguide resonator (9.230x9.230 mm). P1=0.533 mm, P2=0.559 mm, L1=1.000 mm, L2=7.020 mm, W=0.530 mm, S=0.200 mm, G1=0.050 mm, G2=0.530 mm, and G3=0.630 mm. The relative dielectric constant (ε_r) of the substrate is 22. The crosshatched sections represent the HTS material.

to determine the unloaded quality factor (Q_u) of the resonator according to the procedure described in [8]. Before the beginning of each measurement cycle the network analyzer was calibrated with short, open, and load standards.

In order to improve the contact between the launcher and the feed line, silver contacts (~250-300 nm thick) were evaporated onto the end of the feed line and the coplanar ground planes. Immediately after the evaporation the resonators were annealed in flowing oxygen (~1 SLM). The YBCO resonators were annealed at 450°C for 1 hr, and cooled afterwards at a rate of 2°C/min to room temperature. The TBCCO resonators were annealed at 450°C for 10 min, followed by a rapid cooling on a fire brick. The contact resistivity was measured by a three-point probe method, and was found to be ~2.7×10^{-6}, 9.0×10^{-8}, and 4.5×10^{-9} Ωcm^2 for the laser ablated YBCO, the magnetron sputtered YBCO, and the TBCCO films, respectively. The transition temperature ($T_c(R=0)$) of the resonators was measured before and after silver contacts deposition and annealing using a standard four-point probe technique.

III. RESULTS

Table 1 shows a summary of the results of the characterization of the CBCPW resonators. The T_c values and film thicknesses correspond to measurements performed after patterning and annealing of the films. The Q_o's versus temperature of the resonators analyzed in this work are shown in Fig.2.

Table 1. Properties of Conductor-Backed Coplanar Waveguide Resonators at 77 K.

Sample	Film Thickness (nm)	T_c(K)[a]	Q_o[b]	R_s(mΩ)[c]	f_o(GHz)[d]
Au	1200		110	24.0	10.803
1 (YBCO)	310	84.0	159	16.6	10.662
2 (YBCO)	350	91.1	412	6.4	10.805
3 (YBCO)	350	89.9	470	5.6	10.755
4 (TBCCO)	800	103.5	471	5.6	10.742
5 (TBCCO)	800	103.0	577	4.6	10.750
6 (TBCCO)	800	104.2	823	3.2	10.680

[a] dc transition temperature after patterning and annealing.
[b] Unloaded quality factor.
[c] Effective surface resistance.
[d] Resonance frequency.

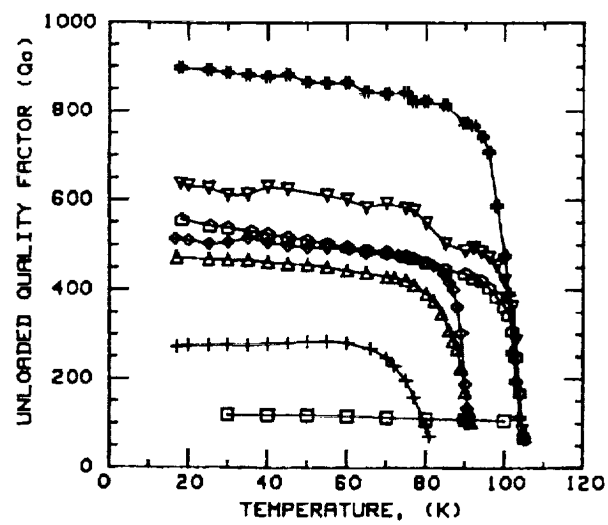

Fig. 2 Unloaded quality factor (Q_u) versus temperature for CBCPW resonators on $LaAlO_3$. Sample 1 (LA YBCO, +), sample 2 (LA YBCO, △), sample 3 (MS YBCO, ◊), sample 4 (LA TBCCO, $\hat{\Delta}$), sample 5 (LA TBCCO, ▿), and sample 6 (LA TBCCO, ╬). A Au resonator (□) is also shown for comparison.

These data were found to be independent of applied power within the range of -5.0 to -26.0 dBm. The lowest Q_u observed in this study for any of the HTS resonator corresponded to a laser ablated (LA) YBCO film (sample 1, Tab. 1). This film exhibited a T_c=84 K after annealing, and although Scanning Electron Microscopy (SEM) micrographs showed a smooth surface, some porosity was noticeable on one of the coplanar ground planes which gave it a hazy appearance. A very smooth surface was also observed for YBCO sample 2, also laser ablated, but not for YBCO sample 3 (magnetron sputtered, MS) which exhibits outgrowths on its surface ranging in size from 1-3 μm. Note that in spite of their different surface morphologies, the Q_u's of these two resonators were comparable which shows that surface roughness does not necessarily equate to a poorer microwave performance, at least for YBCO thin films deposited by the two techniques considered here. This is consistent with microwave results obtained by power transmission measurements in the same type of YBCO thin films [9]. The highest Q_o's amongst the YBCO resonators were exhibited by sample 3. Its Q_o at 77 K was 470 which is ~ 4.3 times better than that of the gold resonator at the same frequency and temperature. This value is lower than reported Q_o's for YBCO-based CPW resonator at the same temperature and at frequencies close to 10 GHz [6]. The lower Q_o may be due to the effect of adding a back conductor to the CPW structure. However, direct comparison between different resonant structures should be done cautiously due to the differences in their geometrical configuration. X-ray diffraction (XRD) analysis showed that the YBCO films considered here have a crystallographic orientation where the c-axis is predominantly oriented perpendicular to the substrate plane. No evidence of change in the XRD patterns was observed for these films after the annealing process.

The TBCCO resonators shown in Table 1. are representative of two different deposition batches, with samples 4 and 5 originating from the same batch and sample 6 from a separate batch. From Fig. 2 it can be seen that the Q_o's for the TBCCO resonators were larger than those obtained for their YBCO counterparts. For the best TBCCO resonator (sample 6, Fig. 2) a Q_o of 823 was obtained at 77 K. This value is ~ 7.4 times that of the gold resonator and is ~1.75 times larger than the Q_o of our best YBCO resonator. It was observed that after the annealing the Q_o's of the resonators increased (almost by a factor of 2 for sample 6) with respect to those obtained before the annealing. The enhanced Q_o's can be correlated with an increase in oxygen content in the films as reflected by the rise in T_c with respect to that measured before the annealing process. For the YBCO films this increase was ~1.0-1.3 K while for the TBCCO films it was ~ 2.0-3.0 K. Observe that for the YBCO resonators (especially for the two laser ablated ones) the discrepancies in Q_o's are well correlated with their T_c values. However, for the TBCCO resonators, although the difference between their T_c values after the annealing was less than 1.3 K, and the temperature at which a measurable resonance was first observed was almost the same (~105 K), still there was a large discrepancy between their respective Q_o's. This difference can be associated with the morphology of the films. The XRD patterns contain only the (00ℓ) reflections for both the 2212 and the 2223 phases. Based upon the relative peak intensities it appears that the films are similar in composition and composed primarily of the 2212 phase. However, SEM analysis revealed that samples 4 and 5 are characterized by a "terrace-like" surface morphology which is absent in sample 6. As such, we believe that the effective thickness of sample 4 and 5 is less than that of sample 6 and thus is responsible for their lower Q_o's.

The effective surface resistance (R_s) for the YBCO and TBCCO HTS films was determined from the unloaded quality factor [10]. The surface resistance of the all-gold resonator was determined from measurements of the dc resistivity (ρ) and using the expression $R_{s,Au}=(\mu_o\omega\rho/2)^{1/2}$, where μ_o is the permeability of free space and $\omega=2\pi f$, where f is the frequency. Values of R_s at 77 K for the HTS-based and all-Au based CBCPW resonators are shown in Tab. 1. Note that the lowest R_s for YBCO is ~0.25 of that for Au, and compares well with those reported by others [6,10] if we assume that the R_s of the superconductor is proportional to the square of the frequency. For TBCCO, our lowest R_s is ~0.13 of that for Au. However, the R_s values obtained in this study for our best TBCCO resonator is ~6 times larger than the value obtained by others from ring resonators fabricated on films from the same source as ours (R_s~6 mΩ at 35 GHz and 77 K; R_s~0.5 mΩ at 10 GHz and 77 K, assuming a $R_s \alpha f^2$) [1]. This may be explained in terms of the current distribution in the conductors of the resonator. In the CPW section of the CBCPW resonator the currents are concentrated near the edges of both the center conductor and the ground planes. Therefore this structure is more sensitive to defects at the edges of the conductors that may arise during the patterning process, resulting in an increase in R_s [11].

IV. CONCLUSIONS

Conductor-backed coplanar waveguide resonators have been patterned on YBCO and TBCCO HTS thin films on $LaAlO_3$. These resonators were tested in the temperature range from 14 to 106 K. Unloaded quality factors Q_o as high as 823 and 470 were obtained at 77 K and 10.8 GHz for TBCCO and YBCO resonators, respectively. The highest Q_o's at 77 K for the TBCCO and YBCO resonators were nearly a factor of 7 and 4, respectively, better than that of an all-gold resonator of the same geometry at the same temperature and frequency. In this study, the Q_o's of the TBCCO resonators were larger than those of their YBCO counterparts throughout the aforementioned temperature range. Our results support the observation that a high T_c does not always correlate with a good microwave performance. In addition, they suggest that the TBCCO films may be the material of choice for cryogenic microwave applications given the fact that there is still room for improvement of aspects such as the porosity of the films. However, more work is necessary to correlate Q_o with porosity for films having similar T_c's.

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